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Are We Alone In the Universe?

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During a summer visit to Los Alamos National Laboratory, most likely in 1950, Enrico Fermi is said to have asked this famous question. The setting was a luncheon with his colleagues, one of whom later recalled bantering, while walking to lunch, about a New Yorker cartoon depicting aliens stealing public trash cans from the streets of New York. The subject was later dropped, but in the midst of lunch, Fermi suddenly shot off his question. He was expressing his surprise over the absence of any signs for the existence of other intelligent civilizations in the Milky Way galaxy.

Fermi estimated that for any reasonable set of assumptions, a technological civilization would have reached every corner of the entire Milky Way within a time much shorter than the age of the solar system. Although many potential resolutions to the so-called Fermi Paradox have been suggested over the years, researchers still have not reached consensus on which one, if any, is correct. Nonetheless, the question of whether we are alone in the Milky Way, or in the universe at large, remains one of the most intriguing questions facing modern humans.

Our solar system formed half way through the history of the universe, and much could have preceded our arrival. Many sun-like stars are billions of years older than our Sun, and many host planetary systems that are similarly very old. The odds of finding evidence for life are completely unknown, but the search continues. Astronomers are observing the nearby universe for distant earth-like planets. We seek potential signs of life on exoplanets that resemble the earth in terms of atmosphere, composition and climate. The next generation of large telescopes in space will provide clues that could include high levels of oxygen and biosignatures of increasing complexity. The answer to "are we alone?" affects nothing less than our claim for being special in the cosmos, and we shall never know unless we search.

How many? Estimates have been attempted of the probability of the existence of intelligent life elsewhere in the universe. They are compounded by our ignorance. There are too many unknowns when it comes to assessing the odds for intelligent life.

Enormous uncertainties are involved with the emergence, evolution, and survivability of any extrasolar life, if it exists. In spite of remarkable progress towards producing life in the lab in recent years, the precise origin of life—the dramatic transformation from chemistry to biology—remains a mystery. Similarly, even though Darwinian evolution has proven to be an enormously successful paradigm for understanding the diversity of life on Earth, the fact that life on earth is the only example of life we have so far, remains a source of extreme unpredictability. This is true particularly in view of the important play of serendipity throughout the history of life on Earth. For example, Earth is blessed with a relatively large moon that has stabilised the climate. The asteroid belt, on one hand, may have helped to seed life, and, on the other, may have been responsible for mass extinctions. Even the location of the solar system within a minor spur off one of the two main arms of the Galaxy, relatively far from the galactic center, has shielded from the potentially sterilizing effects of Gamma-ray bursts.

We have no idea how complex organisms might evolve. There are many random directions that lead nowhere. Darwinian evolution is often invoked. It seems to have worked on the earth. But this could have been an immensely improbable fluke. Environments may be unstable or hostile. Intelligent life may be self-destructive, destined to recycle an infinite number of times, but never to achieve the maturity of million year durations of technology that would allow interstellar travel.

Or intelligent life could have been inevitable, given the billions of years available. Perhaps all we can do is search, since we can't estimate the probabilities involved. Here there is another question: we don't know what to look for. Intelligent life that could accomplish interstellar travel would inevitably be thousands or millions of years ahead of us in technology. Would we even recognise such creatures if they were in front of us? Invisibility cloaks would be a trivial technology for such denizens of the universe, if they exist.

Exoplanets

The topic of extraterrestrial life and how to detect it has become particularly timely. Observations—primarily with the Kepler space observatory—have shown that for every cool dwarf star in the Milky Way, the galaxy contains no fewer than about 0.16 Earth-sized planets orbiting the so-called habitable zone of their parent star. The habitable zone is that "Goldilocks" region that allows for liquid water to exist on the planet's rocky surface. That amounts to more than a billion such planets in our Milky Way galaxy. The Kepler statistics on exoplanets suggest that unless the probability that a habitable-zone planet develops a technological species is exceedingly low—less than 10^{-22} or basically the reciprocal of the expected number of Habitable Zone terrestrial planets in the observable universe—humanity is not the only technological civilization to have ever existed in the universe.

A planet with a minimum mass of 1.3 times the mass of the Earth orbits in the Habitable Zone of the red dwarf Proxima Centauri. At a distance of 4.2 light years, Proxima Centauri is the sun's closest stellar neighbour. Because Proxima Centauri has a mass of only 0.12 solar masses and a luminosity that is only 0.17 % of the solar luminosity, its habitable zone is much closer to the star than is the Sun's habitable zone to the Sun. The newly discovered planet orbits the star in 11.2 days; even so it receives an energy flux that is only about 70% of what the Earth receives from the Sun.

What Is Needed?

Searches for life focus on Sun-like and smaller stars because the vast majority of stars are smaller than the Sun: M dwarfs comprise ~ 70% of all stars in the Milky Way and a large fraction of these M dwarfs harbour planets. Also, more massive stars have shorter lifetimes and emit intense UV radiation. Both factors make them less hospitable as energy sources for biochemical processes that may require billions of years to unfold. Stars more massive than about 3 times the mass of the Sun, for instance, will likely burn out before life has time to emerge and evolve. Red dwarfs, in contrast, are more common and live much longer. As an added bonus planets orbiting and transiting them are easier to detect.

It is simpler to begin by generalizing our search to evidence for life elsewhere. This could be something as simple as microbes. If we found that such organisms existed elsewhere, that would greatly bolster our search for more complex forms of life. The conditions for life require three essential ingredients. We need a solvent such as water. We need organic material. And we need energy.

Water does have a few special characteristics. For example, it is an excellent solvent, it is less dense as a solid than as a liquid; it is amphoteric, which means it can become an acid or a base by donating or accepting a positive hydrogen ion; and it is abundant across the universe. Some form of liquid solvent is undoubtedly necessary if chemicals are to be transported into and out of cells, and molecules are to come into contact with one another to form long-chained organic ingredients. A liquid environment would also protect those organic ingredients from UV radiation. However it is not entirely clear whether only water can play that role.

Oxidization

To be detectable from a distance, however, life has to evolve to the point where it so dominates the planetary surface chemistry that it has significantly altered the atmosphere. Only then will a planet with life give itself away through chemical biosignatures that can in principle be detected remotely. Earth itself would probably not have been detectable as a life-bearing planet during the first billion or more years of its existence. Oxygen, an important biosignature, became an important atmospheric constituent due almost entirely to the simplest photosynthetic organisms, some 2 billion years ago. It built up slowly, first oxidizing rocks. We infer this by finding rusty deposits at the floors of the oceans. By age-dating rocks, we can infer when the oxygen-rich atmosphere developed. Only after prolific oxygen production by biological sources, which made use of energy from sunlight, did free oxygen start to enrich the atmosphere, and only then did primitive multi-cellular precursors of life develop.

How long? On Earth, for example, it took three billion years for the most basic multi-cellular life forms to appear. It took another billion and a half years and an entire series of contingencies, such as plate tectonics and asteroid impacts, to evolve a species capable of rudimentary interstellar communication through radio reception and transmission. We don't know to what extent those timescales reveal any meaningful constraints on the emergence of complex/intelligent life. Nevertheless, they do demonstrate that something dramatic happened once. A challenge for astronomers is to establish whether planetary systems older than the solar system that could maintain a biosphere are common in the Milky Way. Realistically, near-future searches for extra-solar life will concentrate on our Galaxy. But there are tens of billions of galaxies in the observable universe, where life may be lurking.

The current age of the solar system is about half the age of our Galaxy's disk and also half of the Sun's predicted lifetime. We therefore might expect that roughly one half of the stars in our Galactic disk are older than the Sun. That figure by itself, however, is insufficient to judge how commonplace old, biosphere-capable planets are. We need to consider the predicted life span of the biosphere, and not just the lifetime of the host star. For Earth, the biosphere will survive for another billion years or so; then Earth will lose all its water within an additional billion years. Both effects are due to the increasing luminosity of the evolving Sun.

The good news is that these limiting effects do not directly apply to M-type red dwarfs, cooler and lower in mass than the sun. These stars evolve extraordinarily slowly. However, life-hosting planets would still be contingent on geophysical lifetimes, because they must be capable of geochemical cycling. For example, the carbon cycle, the movement of carbon from the atmosphere to land and oceans and back, plays a large part in determining a planet's albedo and temperature, and hence its habitability.

Intriguingly, a recent examination of cosmic planet formation history concluded that the solar system formed close to the median age for existing giant planets in the Milky Way. Consequently, about 80% of the currently-existing Earth-like planets may have already formed at the time of the Earth's formation. This means that they have a head start on the earth of billions of years, in most cases.

Biosignatures

Which *single* detectable biosignature may be considered the most reliable for the existence of life (on a sufficiently old, rocky planet, in the Habitable Zone)? Even though no single biosignature would be absolutely compelling, an atmosphere that is *very* rich in oxygen (say at a level of a few tens of percent) would probably be the most promising target initially. Whereas non-biological processes (such as the splitting of carbon dioxide by intense ultraviolet radiation, or the loss of hydrogen from water vapour) can produce oxygen in a planetary atmosphere, only under rare circumstances would these create such high levels of stable oxygen enrichment. It remains true, however, that only in combination with other potential biosignatures (such as an extreme thermochemical disequilibrium that could be indicated through the simultaneous presence of oxygen and methane), or a determination of the ozone/oxygen ratio, would the credibility of a life-based origin for the oxygen be significantly strengthened.

Searches from Space

An excellent first step in the quest for signatures of extrasolar life in the relatively near future would be to search for planets with atmospheric oxygen in abundance. This can be achieved (in principle) with large, ground-based arrays of relatively low-cost flux collector telescopes (such as a next generation European Extremely Large Telescope, E-ELT; with a collecting area of a few football fields), if those are equipped with very highdispersion (R=100,000) spectrographs. The oxygen lines in the exoplanet's spectrum would be slightly Doppler-shifted relative to oxygen in the Earth's atmosphere, making it possible, though challenging, to detect them. The detection of methane in the infrared would naturally have to follow.

We should note that in the even shorter term, a few upcoming space missions will take a first stab at attempting to detect simple signs of life. The Transiting Exoplanet Survey Satellite (TESS) is expected to be launched in 2018. It is designed to look for planetary transits in front of nearby stars. It is likely to identify about half a dozen relatively nearby transiting super-Earths (exoplanets with a mass of a few times that of the Earth) in the Habitable Zones of M-type (red dwarf, low-mass) stars. Those will be prime targets for further near-IR atmosphere characterization for the 6.5 m diameter James Webb Space Telescope (JWST), also to be launched in 2018. Unless simple life is extremely ubiquitous and easily detectable remotely, however, the probability for the combination of these telescopes to detect life is not very high. The smaller Wide-Field InfraRed Survey Telescope (WFIRST), expected to be launched in the mid- 2020s, will be equipped with a coronagraph, which may enable it to directly image a few super-Earths (or at least sub-Neptune planets). Since imaging measures the planet's albedo (or reflectance), it probes deep into the planetary atmosphere, thus further constraining atmospheric parameters. Still, the chances that WFIRST will actually detect extra-terrestrial life are slim.

What would be the requirements from a space mission to be successful in the search for life? We would want to be able to at least place a meaningful constraint on the rarity of extrasolar life, if such a mission happens to not detect *any* biosignatures. Simulations show that in the case of non-detection, to be able to make a statement such as: "remotely detectable life occurs in less than about 10% of Earth-like planets in the Habitable Zone around Sun-like stars," would require the ability to directly image and characterise the atmospheres of at least three dozen or so exoEarths. Such a yield, in turn, would necessitate a space telescope aperture exceeding 10 meters in diameter, even under optimistic telescope and coronagraph parameters. An ambitious Large UV/Optical/IR (LUVOIR) space telescope. under discussion for the next decadal survey in the US, would be a natural mission candidate to achieve either detection of simple life, or an interesting constraint on its rarity.

There are billions of earth twins in our galaxy. We have many candidates. We need very large telescopes in space to directly image even the nearest of these. Such telescopes are already being planned. The greatest problem is to shade from the overwhelming glare of the parent star. We have to remove this light by a part in ten billion to see an earth-like planet.

Such a star shade is being planned. It is like a giant umbrella made of mylar, but the size of a tennis court, and unfurled in space a million miles from the earth and tens of thousands of meters in front of the telescope. The shade is designed to block the light before it reaches the telescope. The telescope in question would be launched at the same time as the star shade.

Life in the Solar System

A more mundane but essential approach is to look locally in the solar system for signs of extraterrestrial life. Three main ingredients are needed for life. First there is water, a solvent that allows molecules to synthesise. Next there is a non-toxic atmosphere to shield from UV, which destroys life. Finally, energy is required to aid molecules to synthesise.

In the solar system, the Moon and Mercury have no atmosphere. These are not promising environments to search for life. The atmosphere of Venus is toxic: raining sulphuric acid is not compatible with life. Mars is the best bet for seeking traces of fossil life, as it once had a dense atmosphere and its surface is shaped by water and wind-driven erosion that occurred billions of years go. Enceladus, an icy satellite of Saturn, has abundant water, and it is conceivable that its oceans contain life. Other Saturnian satellites, such as Titan, the largest satellite in the solar system, are fascinating worlds to explore, but its methane atmosphere would not be conducive to life as we know it. Methane can be produced organically, and there would be traces of carbon dioxide too. This is not the case for Titan, but its methane haze still serves as a model for astronomers searching for evidence of organic forms of life on young earth-like planets. About 3 billion years ago the earth had a methane-rich atmosphere. Then an explosion of life generated prolific amounts of carbon dioxide which was broken down by UV radiation from the young sun to produce its present oxygen-rich atmosphere.

Signatures of Life

There should be billions of earth-like planets in the Milky Way galaxy. To search for signs of life, we study their atmospheres. The earth's atmosphere shows evidence of plant life. We know this because one can study its light as "earth shine". When there is a crescent moon, light from the earth is seen in reflection. It contains absorption lines seen against the moon light. These show evidence of the "red edge", a feature in the spectrum of light from the earth's atmosphere that is due to UV light being absorbed by vegetation and re-emitted at longer wavelengths. There are even seasonal variations in this so-called red spectral edge, due to the presence of vegetation.. The idea is to search for this feature in the atmospheres of exoplanets in absorption against their parent stars. So far we have not seen this, but detection of the red edge will be a key goal of future telescopes in space. Only these have the necessary resolution in the absence of the earth's atmosphere.

Searching For Intelligent Life

The evolution of intelligent life involves many more open questions. What are the geochemical constraints on the evolution of complex life? On what timescales do those constraints operate? Is there, as it seems, an impetus toward biological complexification? Are there any evolutionary bottlenecks that make it extremely hard to make the transition to intelligence? Are there existential factors that limit the life span of intelligent life?

One would ideally like to go beyond simple biosignatures and seek the clearest sign of an alien technological civilization. This could be the unambiguous detection of an "intelligence"-containing, non-natural signal, most notably via radio transmission or optical/infrared (laser) beaming. The clearest sign of an alien technological civilization could be the unambiguous detection of an information-containing, non-natural signal, most notably via radio transmission. Project SETI is listening, this is the privately-funded Search for Extra-Terrestrial Intelligence, based in California, and taps into radio telescopes that are surveying the universe for other scientific projects. However, so far, no signal has been reported.

To find a sufficient number of candidate planets, one would need to survey many thousands, which puts them hundreds or more likely thousands of light years away. That puts the more probable time for a conversation via responding to transmission of radio signals from another Galactic civilization, assuming one exists, to require a thousand years or more. An interesting suggestion to make the search more efficient argues that we should concentrate on those directions in the sky from which solar mini-eclipses by transiting solar system planets are detectable, since we are more readily discovered by technological civilizations in those directions. We should note, however, that a recent attempt to estimate the fraction of the Galaxy that has been reached by radio communication concluded that only about 1% of the Galaxy has been reached thus far. To give us reasonable odds we might want to reach about 50% of the suitable planets before a signal can be expected. This puts the probable time for a reception of such a radio signal from another Galactic civilization (assuming it exists) some 1,500 years into the future (with considerable uncertainty though).

Similarly, an argument based on Bayesian reasoning (and the possibility that life will emerge in abundance around low-mass stars, trillions of years from now) estimates that the distant future holds much more promise for interstellar communication, intelligent life on Earth having appeared on the cosmic scene rather early. There is, in addition, a distinct possibility that radio communication might be considered archaic to an advanced life form. Its use might have been short-lived in most civilizations, and hence rare over large volumes of the Galaxy or the universe.

Energy Consumption

What might then be a more generic signature? Energy consumption is a hallmark of an advanced civilization that appears to be virtually impossible to conceal. One of the most plausible, long-term energy sources available to an advanced technology is through commanding stellar luminosity with a construction of the type known as a "Dyson sphere", possibly including harvesting the starlight from many stars, not just one, or even from an entire galaxy. The other potential long-term energy source is controlled fusion of hydrogen into heavier nuclei. In both cases, waste heat would be an inevitable outcome, with the consequence of the production of a detectable mid-infrared signature. Even with the expected higher-efficiency energy production of such an advanced civilization, the second law of thermodynamics ensures that some processes are irreversible. A waste heat signal seems inevitable. One concern is that even in the absence of advanced technology, emission from a circumstellar dust belt might confuse any putative signal, but this might be distinguishable spectroscopically.

A recent large survey by the Wide-field Infrared Survey Explorer (WISE) satellite did identify five (but only out of about 100,000) red spiral galaxies whose combination of high MIR and low near-ultraviolet luminosities are seemingly inconsistent with simple expectations from high rates of star formation. The UV luminosity, which is dominated by young stars, typically tracks the star-formation rate, while the infrared luminosity, which is dominated by the much more abundant low-mass stars, tracks the total stellar mass. A conventional explanation for these observations, however, such as the presence of large amounts of internal dust, has not been ruled out. Such peculiar objects definitely deserve follow-up observations before we explore whether they might represent the signature of galaxy-dominating species.

A star that has been in the news recently is KIC 8462852. This star has shown unusual fluctuations in brightness, sometimes dipping by as much as 22% for periods of just a few days, as well as a gradual decline (by about 14% over a century). The speculation has therefore been that these fluctuations may represent the presence of some "megastructure" (such as a Dyson sphere) being constructed around the star. A more plausible scenario is that we are observing the decline phases after a brightening that resulted from the star having "swallowed" a planet or an asteroid.

Short-Lived Signatures

Other potential signatures of technological civilizations that have been suggested, such as various forms of atmospheric industrial pollution, or short-lived radioactive products, are necessarily transitory. Basically, we expect that aliens either learn how to clean up their act or they destroy themselves. Infrared emission, on the other hand, seems almost unavoidable. Note that the anticipated IR signal should be a non-negligible fraction of the luminosity of a star, and should far exceed typical reflections from terrestrial planetary surfaces and atmospheres.

More pessimistically, biologically-based intelligence may constitute only a very brief phase in the evolution of complexity, followed by what a few futurists have dubbed the "singularity" - the dominance of artificial, inorganic intelligence. If this is indeed the case (many regard this as an unsubstantiated projection), advanced species are likely not to be found bound to a planet's surface, where gravity is helpful for the emergence of biological life but is otherwise a liability, but rather floating in space. Given this imaginative conjecture about the distant future, one can still argue that any surviving species must be near a fuel supply, namely a star, because of energy considerations. Even if such intelligent machines were to transmit a signal, it would probably be unrecognizable and non-decodable to our relatively primitive, organic brains.

Other transient signals may be more promising. Nuclear war is another source of atmospheric pollution, but short-lived. Industrial pollution is around for a much longer time. Life is remarkably resilient. Allowing for the worst excesses of nuclear war, global warming or major asteroid impact, advanced life would regenerate over tens of thousands of years. Unless society completely self-destructs, the duty cycle for regeneration of advanced intelligent life may be as much as 10%. This means that we might expect to need 1000 years of civilization, roughly the time since William the Conqueror on earth, for humanity to approach a climax for auto-destruction, that would set civilization back to the level of the Middle Ages, or even, in a worst case scenario, back to the Stone Age.

However life is incredibly resilient. It exists in volcanic craters and in the deepest depths of the oceans. This disaster should followed by 5000 to 10000 years for regeneration to a new state of humanity, capable of the highest levels of philosophy and poetry, of art and science, but equally of devastating war, of interplanetary travel and inevitably, subject to high existential risk.

This could perhaps explain the Fermi Paradox. If this scenario holds true, our chances of detecting simple life may far exceed those of discovering intelligent ETs (even if intelligent life is ubiquitous). Still, the ultimate goal of detecting the signature of an advanced intelligence, whether biological or nonbiological, remains the most intriguing option. All power to proposed projects for the 2020s such as Japan's Space Infrared Telescope for Cosmology and Astrophysics (SPICA) and NASA's Far Infrared Surveyor.

The key point is that *for the first time in human history, we are perhaps only a few decades away from being able to actually answer the "Are we alone?" question.* A possible pathway towards this inspiriting goal may include the following steps: The detection of potential signs of life with the upcoming generation of space telescopes, followed by the detection of high levels of oxygen from large ground-based telescopes and biosignatures of increasing reliability with the next generation of 10m-class telescopes in space. Simultaneously, searches for electromagnetic signals from other Galactic civilizations should continue, and searches for unusual infrared emission (that could indicate energy consumption by remote species) should be intensified.

The Proactive Approach: Let's Go There

The nearest planets are about 4 light years away, around the star Proxima Centauri. This is close enough so we can imagine sending space craft there. One would need to have a space craft capable of travel at a tenth of the speed of light. This is technically feasible for propulsion by a light sail. This works by the effect of intense beams of light on what is effectively an interstellar sail attached to space craft.. The light could be from a bank of lasers on the earth. Continuous pressure of light results in the velocity of the space craft approaching near light speed.

The scheme has been studied, and is feasible for sufficiently tiny space craft. The typical mass of the device is a few grams, in the form of a sophisticated electronic micro-camera. This is implanted in a gram-scale silicon wafer propelled by a light sail. The only practical means of interstellar transport utilises light sails. Project Breakthrough Starshot intends to launch thousands of micro-cameras to Proxima Centauri. Propelled by banks of 100 gigawatt lasers, thousands of micro-cameras would arrive at Proxima Centauri after a journey of 40 years. Four years later, we might have high resolution images of the nearest exoplanets.

Because the answer to "Are we alone?" may affect nothing less than our claim for being special in the cosmos, its importance cannot be overemphasised. In any case, we shall never know unless we search!

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